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Cristi, R.

ADAPTIVE IDENTIFICATION AND CONTROL OF AN AUTONOMOUS UNDERWATER VEHICLE

R. Cristi *, A.J. Healey **

*Dept. of Electrical and Computer Engineering
**Dept. of Mechanical Engineering
Naval Postgraduate School, Monterey, CA 93943

Abstract An adaptive controller for dive maneuvering of a submersible is presented. Main feature is that it performs adaptive pole placement of the closed loop system, based on the estimated dynamics. While the linear compensator adapts in the presence of changing operating conditions, a nonlinear controller along the lines of the Variable Structure (VS) approach guarantees robustness in the presence of nonlinearities and unmodelled dynamics.

1. Introduction

Dynamic models for underwater vehicles are highly nonlinear, and robust, nonlinear and/or adaptive techniques are currently considered in the design of autopilots for fast maneuvering. Autonomous Underwater Vehicles may have to respond quickly and precisely in order to avoid external uncharted obstacles. They should be able to perform fast diving and turning maneuvers in response to reflexive commands from the path planner and the obstacle avoidance system.

Various approaches have appeared in the literature. Mainly controllers based on robust model following control [1], [2], with reduced order models [3], and nonlinear Variable Structures (VS) [4], [5] have shown to be effective to cover a wide range of operating conditions of underwater vehicles.

At the same time the theory of Adaptive Control systems [6] has progressed considerably, and marine applications such as the steering of tankers have been proven successfull [7]. Problems of instability in the presence of unmodeled dynamics and nonlinearities, and/or external disturbances have been addressed in the literature [8] and robust adaptive controllers redesigned.

In this paper we present an adaptive controller for application to diving maneuvers of submersible vehicles. The controller is based on the fact that the dynamics of the vehicle are close to linear within ranges of operating conditions (defined by constant speed), and is made robust by the addition of a VS input based on bounds (assumed to be known, or guessed) of the nonlinearities. Although full state measurement (pitch, pitch rate, depth) is required by the controller, it is shown that for a general class of systems - Almost Strictly Positive Real (ASPR) [9], the controller can be designed on the basis of input-output signals alone (say dive plane command and depth).

In Section 2 we address the modeling problem in terms of identification of an Autoregressive with External input (ARX) model, while in section 3 we present the adaptive controller. In section 4 the problem of using input output signals alone is discussed and some results presented. Finally computer simulation results are shown in section 5.

2. Identification of the Mathematical Model.

Mathematical models describing the dynamics of submarines exist in many forms. The model considered in this report is based on the equations of motion for a six degree of freedom underwater vehicle developed by Gertler and Hagen [10] which describes the motion of a body of revolution. Modifications of these equations by Smith, Crane and Summey [11] to represent the shape of a flat, smooth vehicle shown in figure 1 have been simulated by Boncal [2] and a reduced version has been developped by Larsen [12]. The general three dimensional equations of motion are developped on a right hand coordinate system with velocity components $[u, v, w, p, q, r]$ in the body fix frame and position components $[x, y, z, \phi, \theta, \psi]$

in the global reference frame. For a diving maneuver we limit the dynamic equations relative to the state vector $x = [q, \theta, z]$ of pitch rate (q), pitch (θ) and depth (z), and stern dive plane command δ as

$$\dot{x} = \phi(x, \delta) \tag{2.1}$$

In spite of the highly nonlinear behaviour of the submersible dynamics, it has been shown [13] that linearization around operating conditions (defined by constant desired forward speed) can be used for the control design problem. In particular we can separate the linear and nonlinear components of ϕ in (2.1) and write

$$\dot{x} = \begin{bmatrix} -a_1 & -a_2 & 0 \\ 1 & 0 & 0 \\ 0 & -v & 0 \end{bmatrix} x + \begin{bmatrix} b \\ 0 \\ 0 \end{bmatrix} + f(x) \tag{2.2}$$

where v is the forward velocity and the nonlinear term f is relatively small. The linear part of the model is shown in figure 2 where the feedback term K accounts for the restoring moment of the centers of gravity and buoyancy being displaced by a change of pitch angle.

A linear model can be estimated by a standard Recursive Least Squares or an Instrumental Variable algorithm by assuming an ARX discrete time model

$$A(q^{-1})y(kT) = B(q^{-1})u(kT) + e(kT) \tag{2.3}$$

A, B being polynomials in the time delay operator ($q^{-1}y(kT) = y(kT - T)$, T being the sampling interval), and e a random error sequence, possibly colored. The output of the linear (estimated) and nonlinear models pitch rate are shown in figure 3 for a twin screw vehicle of 17.4 feet in length weighing 1200 pounds operating at 500 rpm. Also the estimated dynamics at different operating conditions in terms of estimated poles and zeros in the z plane are shown in table 1. The effect of the restoring moment (gain K) being more dominant at lower speeds can be seen from the poles becoming complex.

Based on the time varying linear model of the AUV and bounds on the nonlinearities f, a controller is designed which adapts to the different operating condiitons.

3 Adaptive Control of the AUV

In this section we present a controller based on the dynamics (2.2) which combines adaptivity to place the eigenvalues of the linear section, and a switching input to compensate for the nonleariry $f(x)$. This controller can be considered as an extension of a standard adaptive controller for linear dynamics, made robust by a Variable Structure (VS) control in the presence of nonlinear dynamics. As in the VS techniques the state vector is driven toward a linear subspace of the form $s^T x = 0$, for some vector s, using both the switching input and the adaptive compensator.

In the depth control case the goal of the controller is to drive the submersible to a desired depth z_d (constant) and maintain it in the presence of external perturbations. By writing the dynamical model (2.2) as

$$\dot{x}(t) = Ax(t) + b\delta(t) + f(x) \tag{3.1}$$

with A, b in controllable canonical form, due to the presence of an eigenvalue at zero in the A matrix, we can define the error vector

$$e(t) = [q, \theta, (z - z_d)/(-v)]^T \tag{3.2}$$

between the desired $[0, 0, z_d/(-v)]$ and actual states, and write the model in terms of the error state

$$\dot{e}(t) = Ae(t) + b\delta(t) + f(e) \tag{3.3}$$

Alternatively for any given matrix A_m in companion form with eigenvalues in the stable region, representing desired closed loop dynamics, we can write (3.3) as

$$\dot{e}(t) = A_m e(t) + b(\delta + K^T e(t)) + f(e) \tag{3.4}$$

with K depending on the vehicle dynamics.

The dynamic model (3.4) is the basis of the adaptive controller presented below, aiming at stabilizing the vehicle on a dive command, and driving the error state $e(t)$ to zero in the presence of uncertainties in the open loop dynamics (represented by K and $f(e)$).

In particular we can show the following:

a) Let (λ, c^T) be a pair of real eigenvalue (λ) and corresponding left eigenvector of the matrix A_m in (3.4) such that $c^T b \neq 0$ (assume $c^T b > 0$). The existence of c is guaranteed by the pair (A_m, b) being completely controllable [14];

b) Let a bound F on the nonlinearity f be known as

$$F(e) > |c^T f(e)/c^T b| \tag{3.5}$$

c) Bounds on the gains K in (3.4) be known as

$$K_i^m < K_i < K_i^M \tag{3.6}$$

with K_i the elements of K.

Then the control input

$$\delta(t) = -\hat{K}^T(t)e(t) - F(e)sgn(s(t)) \tag{3.7}$$

with

$$s(t) = c^T e(t) \tag{3.8}$$

and the adaptive gains

$$\dot{\hat{K}}(t) = -\sigma(\hat{K}(t)) - \mu e(t)s(t) \tag{3.9}$$

with [8]

$$\sigma_i(\hat{K}) = \begin{cases} 0 & \text{if } K_i^m < K_i < K_i^M \\ -\alpha\hat{K}_i(t) & \text{if } K_i(t) < K_i^m \\ -\alpha\hat{K}_i(t) & \text{if } K_i(t) > K_i^M \end{cases} \tag{3.10}$$

α being a positive constant, is such that the closed loop system is exponentially stable and

$$\lim_{t->\infty} e(t) = 0 \tag{3.11}$$

for any initial conditions.

Proof. From (3.7), (3.8) we can write (3.4) as

$$\dot{s}(t) + \lambda s(t) = c^T b\tilde{K}(t)^T e(t) + c^T f(e) - c^T bF(e)sgn(s(t)) \tag{3.12}$$

with $\tilde{K}(t) = K - \hat{K}(t)$ the parameter error. Define the Lyapunov function

$$V(s, \tilde{K}) = \frac{1}{2}(s^2 + \frac{c^T b}{\mu}\tilde{K}^T\tilde{K}) \tag{3.13}$$

and its time derivative along the trajectories of (3.12) can be computed as

$$\dot{V}(s, \tilde{K}) = -\lambda s(t)^2 - (c^T bF(e) - c^T f(e))s(t) - \frac{c^T b}{\mu}\tilde{K}(t)^T\sigma(\hat{K}(t)) \tag{3.14}$$

It is easy to see from the definition of σ in (3.10) that the rightmost term in (3.14) is such that

$$\tilde{K}(t)^T \sigma(\hat{K}(t)) \geq 0 \tag{3.15}$$

which yields $\dot{V} \leq 0$. Therefore $\tilde{K}(t)$, $s(t)$ are uniformly bounded, and furthermore $s(t) \in L_2$, the set of signals square integrable. This fact and boundedness of the derivative $\dot{s}(t)$ implies that $s(t) -> 0$ as $t -> \infty$.

Finally (3.11) follows from the fact that

$$e(t) = [e^{(2)}(t), e^{(1)}(t), e^{(0)}(t)]^T$$

with $e^{(0)}(t) = z(t) - z_d(t)/(-v)$, $e^{(j)}$ its derivatives and the entries of the vector c being coefficients of a Hurwitz polynomial. The latter comes from the left eigenvectors being orthogonal to the right eigenvectors $[\lambda_i^{n-1}, ..., 1]^T$ of the matrix A_m corresponding to the other eigenvalues λ_i.

4. Adaptive Control with Input Output Signals

The adaptive controller with variable structure presented above assumes that measurements of the state of the system are available. In this section we address the problem of designing a robust adaptive controller based on the measurements of input output signals only. Let us consider a SISO system of the form

$$y(t) = \frac{b_1 B(D)}{A(D)} u(t) + f(u, y, t) \tag{4.1}$$

with A,B monic polynomials in the differential operator $D = d/dt$, and f the nonlinear term of known bound. As a particular case let $deg(A) = deg(B) + 1 = n$ and let B be a Hurwitz polynomial. By the solution of the Diophantine Equation [14] it is possible to verify that given any constant λ we can determine two polynomials of degree $n-1$ such that we can write (4.1) as

$$(D + \lambda)y(t) = b_1(u(t) - K_1(D)\tilde{u}(t) - K_2(D)\tilde{y}(t) + \bar{f}) \tag{4.2}$$

where $\tilde{u}$, $\tilde{y}$ are filtered input output signals as

$$Q(D)\tilde{u}(t) = u(t)$$

$$Q(D)\tilde{y}(t) = y(t)$$

Q being the observer polynomial Hurwitz of degree n. The two polynomials K_1, K_2 in (4.2) can be computed from the standard pole placement problem for a closed loop characteristic polynomial given by $(D + \lambda)B(D)$.

By an argument identical to the one presented in the previous section we can determine an adaptive controller for (4.1) based on (4.2) which drives the output signal y to zero.

Although the case just discussed is too restrictive to be of a significant use (most cases of interest do not have a relative degree of one), it can be extended to a more general class of problems. In particular we call the systems (4.1) minimum phase with relative degree of one as Almost Strictly Positive Real (ASPR) [9] since we can obtain a Strictly Positive Real (SPR) system by feedback. In our case it is evident from (4.2) that the input $u(t) = k_1(D)\tilde{u}(t) + K_2(D)\tilde{y}(t) + \bar{u}(t)$ yields the closed loop dynamics $(D + \lambda)y(t) = \bar{u}(t)$ when the nonlinear term $\bar{f}$ is zero.

It is possible to show [9] that a wide class of systems can be made ASPR by parallel connection. In particular (as derived from [9])

Lemma: given the strictly proper transfer function $G(D)$ of order n, let $H(D) = \frac{M(D)}{N(D)}$ be a nonproper transfer function with $deg(M) = deg(N) + 1$ such that $GH/(1 + GH)$ is exponentially stable. *Then* $G(D) + H(D)^{-1}$ is ASPR.

In conclusion by ***augmenting*** the system G by H^{-1} the combined system is ASPR, and the combined output can be driven to zero by the technique described in this paper.

5. Simulation Results

The adaptive algorithm presented in the previous sections has been simulated in several diving maneuvers, using the model of Gertler and Hagen [10]. Figures 4 and 5 compare actual and desired depth at 300 and 500 rpm, together with the adaptive gains, and the signal $s(x) = c^T e$ in (3.8) driving the controller. From these and various simulations it can be seen that tracking of the depth signal is obtained for different operating conditions. The adaptive gains provide for the necessary stabilizing action, together with the VS input.

6. Conclusions

An adaptive control algorithm for diving maneuver of a submersible vehicle has been presented. Main feature is that it is robust in the presence of nonlinear and unmodelled dynamics of known bound, and is of simple implementation. An extension to the case of output feedback is also discussed, applicable to cases when the state signals are not available.

7. Aknowledgement:

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Dive Model	Parameters	H(z)
500 rpm	$a_1 = 1.608 \quad b_1 = -0.082$ $a_2 = -0.625 \quad b_2 = 0.081$	$\frac{(z-0.991)}{(z-0.949)(z-0.659)}$
300 rpm	$a_1 = 1.726 \quad b_1 = -0.035$ $a_2 = -0.743 \quad b_2 = 0.035$	$\frac{(z-0.989)}{(z-0.908)(z-0.817)}$
100 rpm	$a_1 = 1.746 \quad b_1 = -0.0120$ $a_2 = -0.767 \quad b_2 = 0.012$	$\frac{(z-0.973)}{(z-0.873 \pm 0.068j)}$

Table 1: estimated second order dynamics (dive plane to pitch rate)

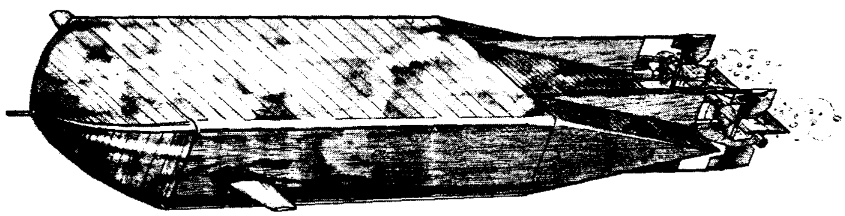

Figure 1: view of the vehicle

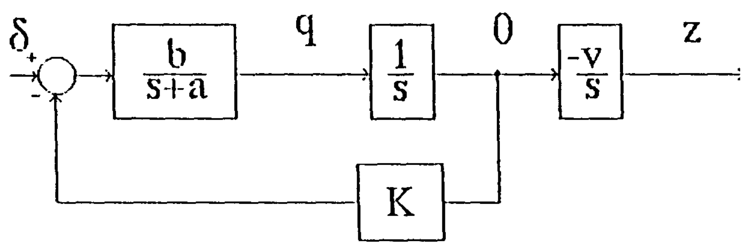

Figure 2: linear model

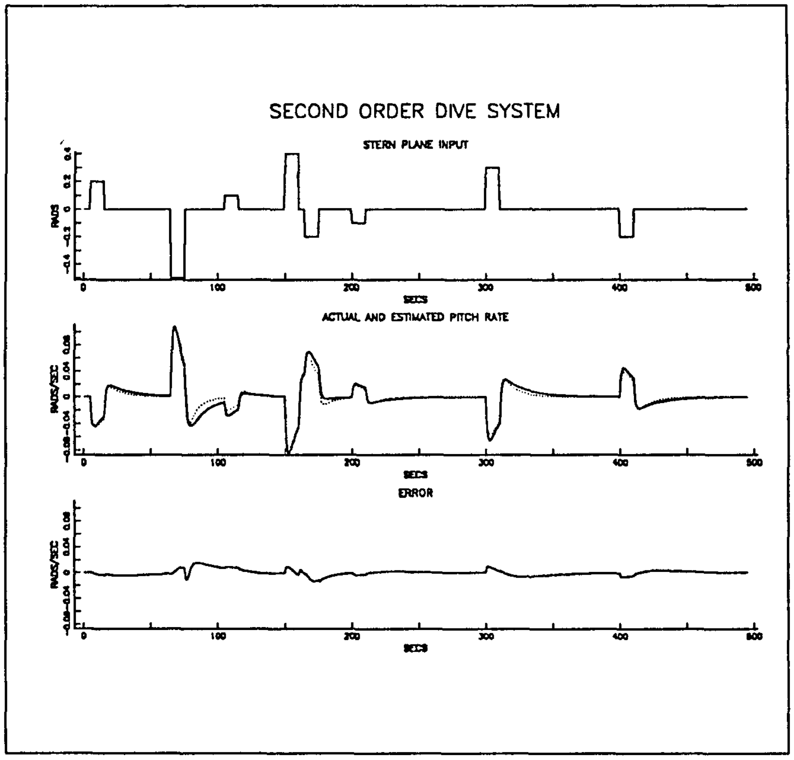

Figure 3: pitch rate (actual and modeled)

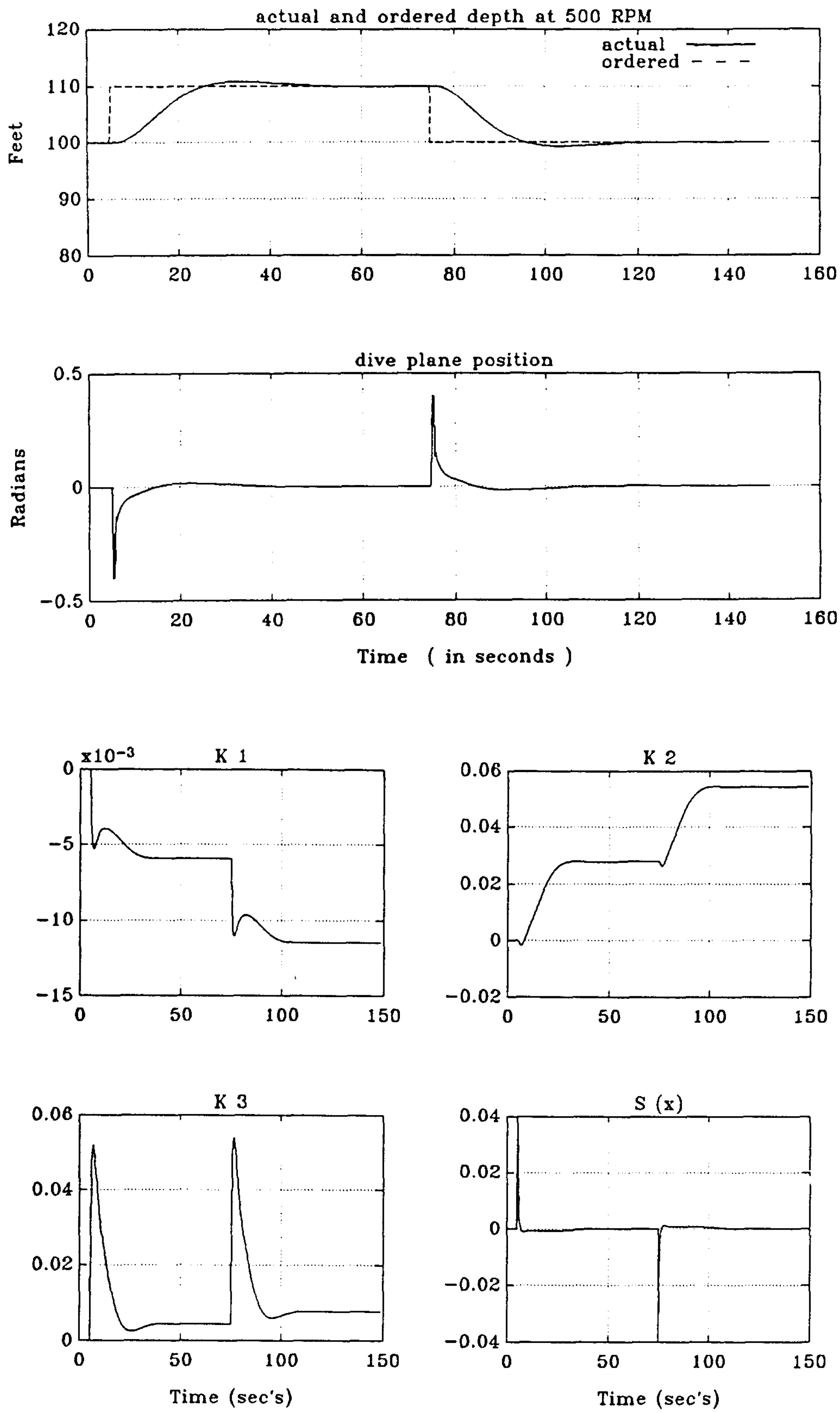

Figure 4: diving maneuver (500 rpm)

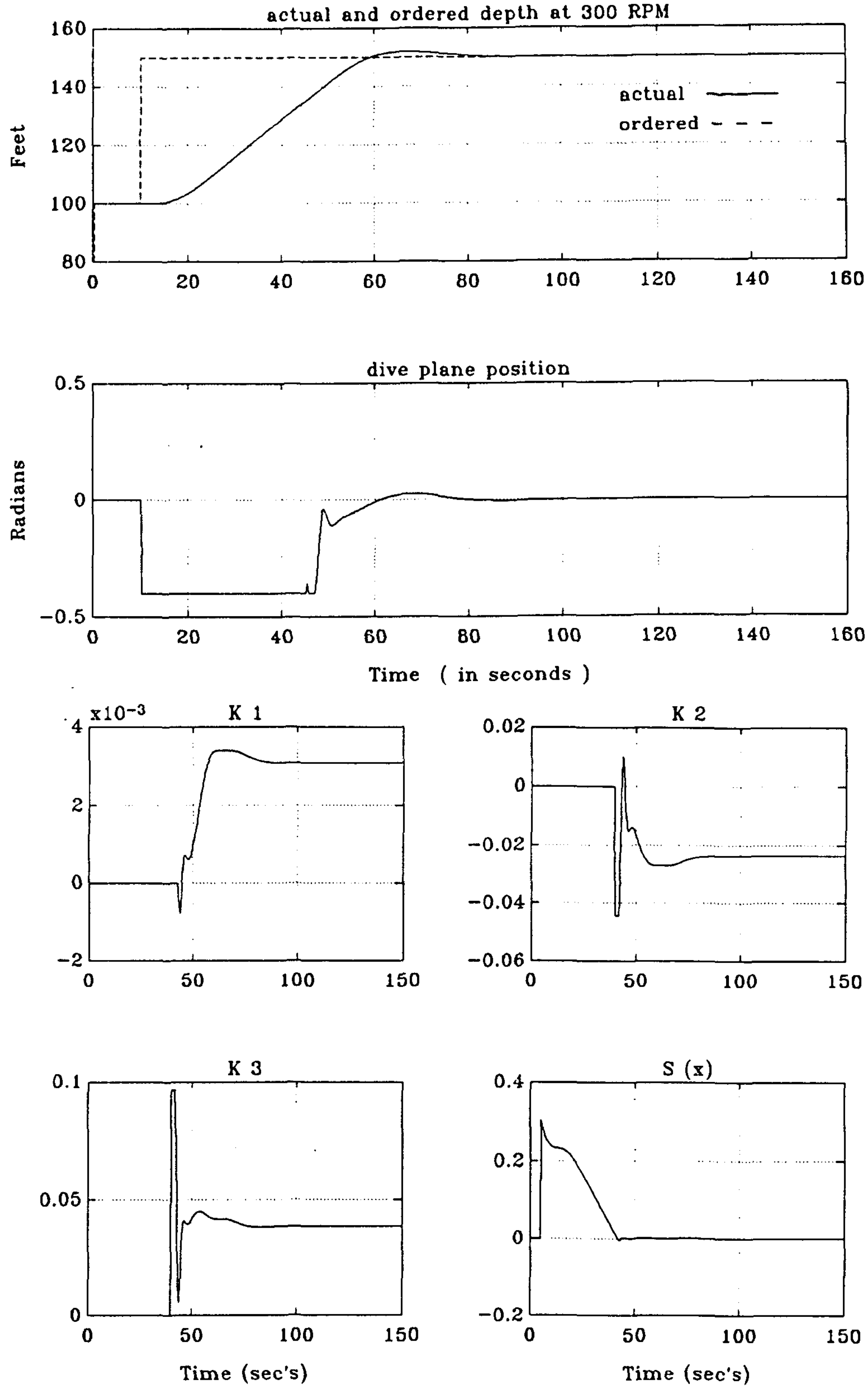

Figure 5: diving maneuver (300 rpm)